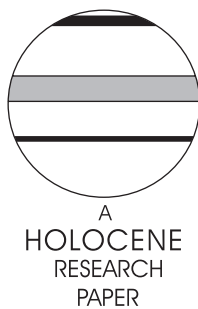


Late Quaternary river evolution of floodplain pockets along Mulloon Creek, New South Wales, Australia

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Abstract: Valley confinement along upper–middle reaches of Mulloon Creek, in the upper Shoalhaven catchment of southern New South Wales, Australia, restricts floodplain development to a series of distinct pockets. These pockets comprise a downstream-thinning wedge of vertically accreted fine-grained deposits atop basal gravels. Some time before 12 500 years ago a bedload-dominated river was transformed into a suspended load system. In the mid–late Holocene, swamps developed in the middle–lower part of each floodplain pocket. Within a few decades of European settlement of this region (circa AD 1820), discontinuous watercourses in some floodplain pockets had incised to form a low-sinuosity gravel-bed channel. Wedge-shaped units of post-incisional alluvium that thicken downstream overlie the swamp and floodplain deposits in the downstream part of these pockets. In the downstream-most pocket, incision commenced prior to colonization, while upstream swamps retain a continuous swamp across the valley floor. The late Quaternary evolution of this variant of discontinuous watercourse is summarized in a schematic model.

Key words: Discontinuous watercourse, incised channel, swamp, floodplain pocket, river change, alluvium, late Quaternary, Holocene, New South Wales, Australia.

Introduction

Over the last decade or so, various studies have demonstrated the variable manner and rate of river response to human disturbance across Australia (see review by Rutherford, 2000). At the time of European settlement, many broad valleys of low relief, upland landscapes in southeastern Australia comprised a range of types of discontinuous watercourses, including chains of ponds (Eyles, 1977), dells (Young, 1986) and swampy meadows (Prosser *et al.*, 1994). Throughout the Holocene, at least, these cut-and-fill landscapes have been subjected to multiple phases of incision and sedimentation, in a similar fashion to arroyos of the American Southwest (Cooke and Reeves, 1976) or semi-arid erosional systems in the Mediterranean region (Vita-Finzi, 1969), among many variants. Typically, phases of sedimentation across unchannelized valley floors lasting thousands of years are separated by much shorter intervals (typically decades or centuries) of channel incision and expansion (Prosser *et al.*, 1994; Prosser and Winchester,

1996). The extent and rate of incision and expansion have been greatly enhanced by human disturbance. Today, many of these upland floodplains, swamps, chains of ponds and dells are deeply incised and have broad continuous channels. These former zones of sediment accumulation and long-term storage have been transformed into source and transfer zones (eg, Brierley and Murn, 1997; Fryirs and Brierley, 2001).

Major river changes in southeastern Australia during the late Quaternary (past ~125 ka) reflect remarkable changes in flow regime along rivers that were not affected by headwater glaciation (Nanson *et al.*, 1992, 2003; Nott *et al.*, 2002). Cyclical but generally declining episodes of fluvial activity are indicated during the past full glacial cycle. Evidence for various phases of powerful river activity in the late Pleistocene is preserved in gravel materials exposed in terraces. The period from 12 to 3 ka BP was marked by much lower flows than those of the late Pleistocene, but they were certainly more pronounced than those of today (Nanson *et al.*, 2003). Profound changes to river morphology accompanied the decline in river activity throughout the Holocene (see Nanson *et al.*, 1992, 2003; Prosser *et al.*, 1994; Nott *et al.*, 2002) and, since about 3–2 ka BP, many rivers in coastal southeastern

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Australia have been laterally stable (Nanson *et al.*, 2003). Many channels operate in a relatively narrow belt within laterally extensive valley floors, effectively inset within coarser-grained alluvial units. Land clearance since European settlement has dramatically destabilized many of these rivers (eg, Brooks *et al.*, 2003).

In this study, detailed field mapping, sedimentological investigations and a series of conventional and AMS radio-carbon ages, are used to document the late Quaternary history of four floodplain pockets along Mulloon Creek, an upland tributary of the Shoalhaven River in southern New South Wales (Figure 1). The pattern and history of sedimentation in these floodplain pockets, which are separated by bedrock-confined reaches, demonstrate an intriguing extension to previously documented variants of discontinuous watercourses.

Regional setting

Mulloon Creek drains an area of 400 km² in a north–south aligned subcatchment of the Upper Shoalhaven River in the Southern Highlands of New South Wales (Figure 1). The area forms the far southeastern part of the Lachlan Fold Belt, and comprises complex folded Ordovician, Silurian and Devonian metasediments and Devonian granites (Felton and Huleatt,

1976; Scheibner, 1998). The lithology and faulting history have resulted in irregularly spaced elongate floodplain pockets of varying size in a ‘beads on a string’ configuration (Figure 1). Each floodplain pocket is confined by bedrock at its upstream and downstream ends. Four pockets are studied in this manuscript, labelled ‘Galvin’s Valley’, ‘Ralpine Valley’, ‘Mulloon Creek’ and Lower Mulloon on Figure 1. Primary geomorphic attributes of each floodplain pocket are summarized in Table 1.

The study area has a temperate, subhumid to humid climate with a mean annual rainfall of 600–800 mm, reaching 1000 mm in the local ranges (Jenkins, 1996). Average maximum monthly temperatures range from 7–25°C in January to 0–11°C in July. There is no evidence in the region of extensive modification of eucalypt forests associated with aboriginal use of fire (Costin *et al.*, 1984). However, dramatic changes to land cover accompanied European colonization of the area, which commenced in the early 1820s. Much of the original vegetation on the surrounding hills was cleared for grazing and agriculture. Some regrowth has occurred in less productive areas. In the past, hardwood logging was carried out in forests on the ranges to the south and southwest, but much of this area now forms part of a National Park. Most floodplains and low hills are now covered by grassland with sporadic patches of open to low open forest (dry sclerophyll

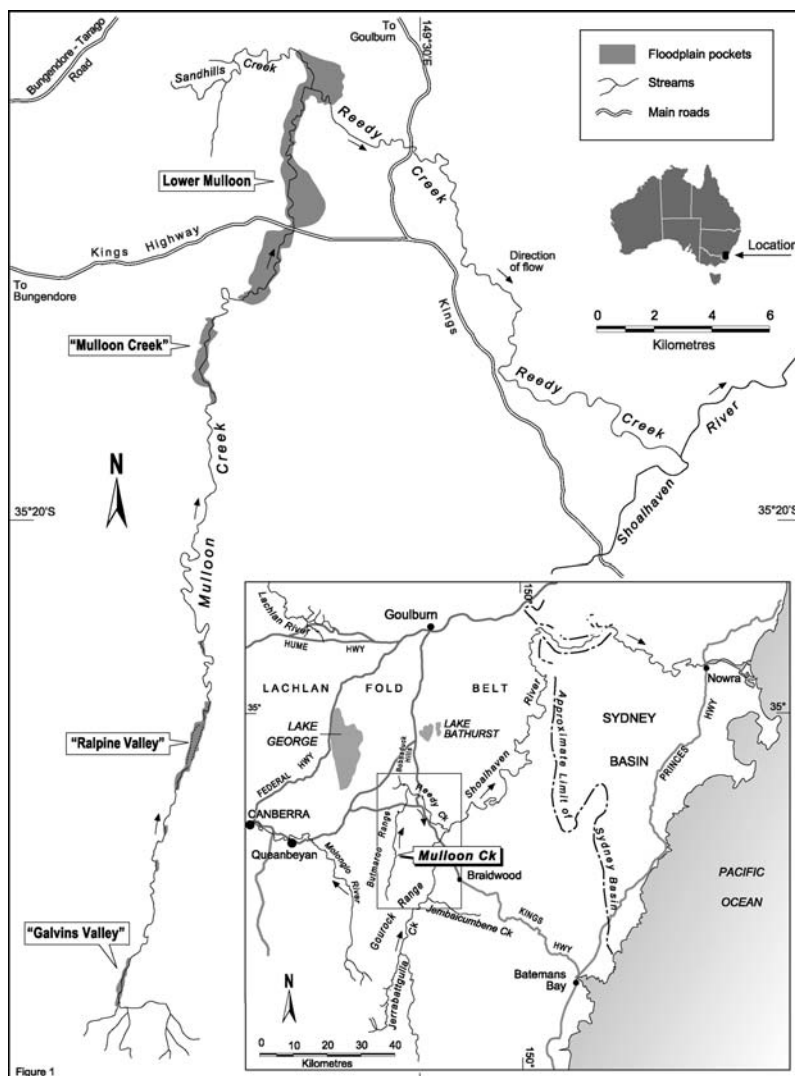


Figure 1 Study area, showing location of floodplain pockets

Table 1 Attributes of floodplain pockets on Mulloon Creek

Floodplain pocket	Distance from source (km)	Dimensions				Bed material size (b_{max} (cm))
		Length (m)	Width (m)	Area (ha)	Slope (mm^{-1})	
'Galvin's Valley'	2.5	1300	150	36	0.0186	10
'Ralpine Valley'	7.4	3500	160	95	0.0045	48
'Mulloon Creek'	20.8	2400	280	113	0.0025	8
Lower Mulloon South	24.2	3200	480	252	0.0044	15
Lower Mulloon North	27.3	6900	960	756	0.0029	14
					0.0025	

forest) (Jenkins, 1996). Patches of willows have been planted adjacent to incised streams in an effort to control bank erosion.

Methods

Geomorphological maps were produced at a scale of 1:25 000 for each floodplain pocket using stereo aerial photographs and field mapping. Recent river adjustments were appraised from historical air photographs, portion plans dating back to the 1820s, and information from local historians and historical societies. This was complemented by detailed sedimentological investigations at representative bank exposures and floodplain cores. The upper units of selective floodplain sequences were analysed for excess ^{210}Pb content by the Australian Nuclear Science and Technology Organisation (ANSTO). Charcoal and wood samples extracted from other floodplain and channel fill sequences were radiocarbon dated (conventional and AMS) at the University of Waikato Laboratory. Bed material sizes along floodplain pockets were analysed using b-axis measurements of 100 clasts recorded at 1-m spacing in the coarsest depositional unit of any given subreach. The longitudinal profile of the channel bed and multiple cross-sections of each pocket were surveyed.

Results

'Galvin's Valley'

'Galvin's Valley' lies 2.5 km from the headwaters of Mulloon Creek in Tallaganda State Forest (Figures 1 and 2). The surrounding catchment has not been cleared for agriculture. Valley fills are less than 2 m deep. At the upstream end of the pocket Mulloon Creek has a continuous channel, approximately 2 m wide and 1.5 m deep. Moving down-pocket, channel size decreases, ultimately disintegrating into multiple discontinuous channels, with small pools, which flow through and between the lush vegetation of an intact swamp. At the downstream margins of the swamp, channels have locally incised almost 1 m. Thin, poorly sorted, matrix supported, pebble and gravel deposits overlie bedrock. The lack of organic-rich fine-grained materials in core GV1 indicates that the swamp did not extend down-pocket from its present position (Figure 2).

'Ralpine Valley'

'Ralpine Valley' is an elongate floodplain pocket 3.5 km long and 150 m wide located 7.4 km from source (Figures 1 and 3). Like 'Galvins Valley', this pocket is surrounded by deeply dissected, well-forested slopes of Tallaganda State Forest. At the exit from confinement, a strath terrace lies around 20 m above the contemporary channel, but by mid-pocket this feature is being buried by swamp deposits.

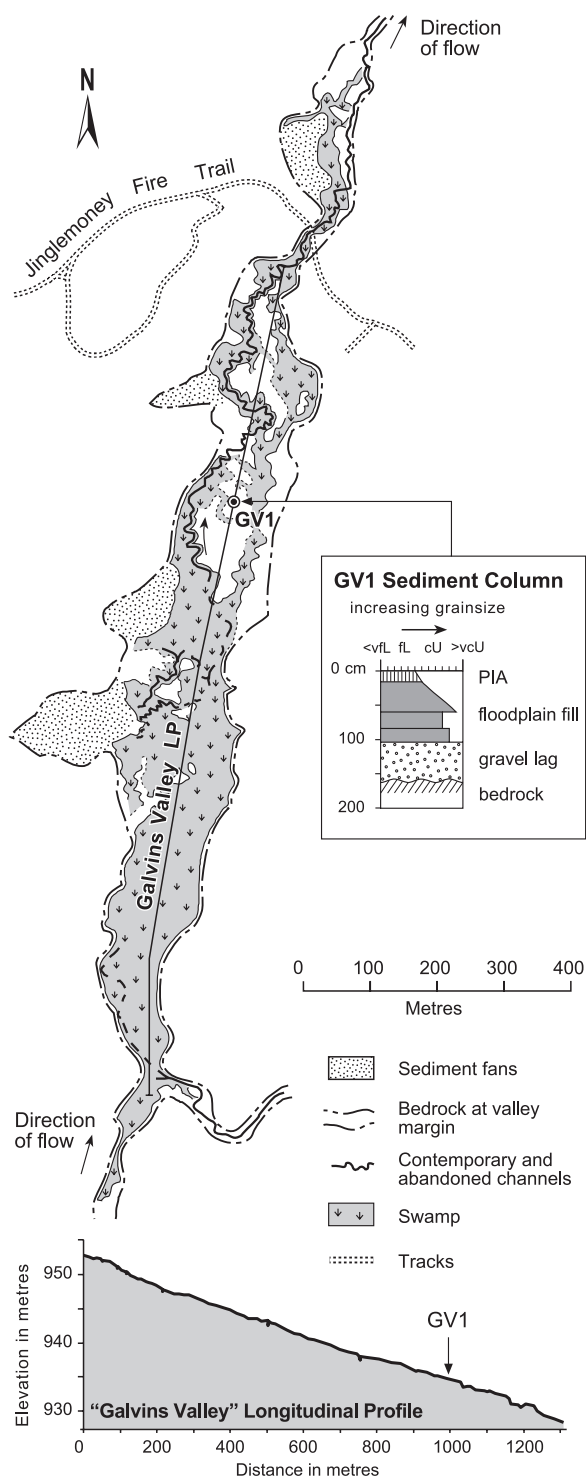


Figure 2 Distribution of geomorphic units at 'Galvin's Valley' showing the long profile (inset) and core location. PIA refers to post-incisional alluvium, as discussed later in the text

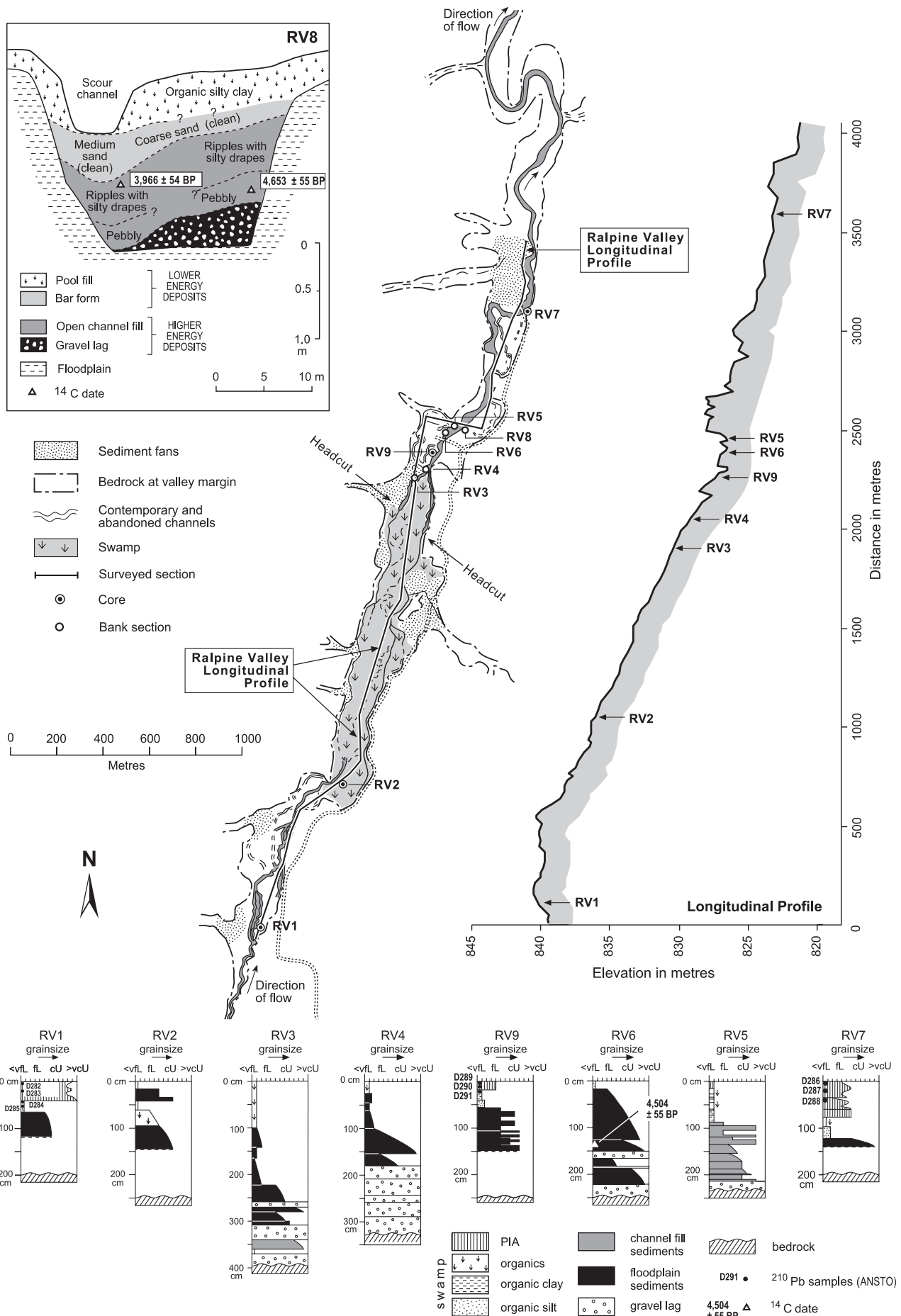


Figure 3 Distribution of geomorphic units at 'Ralpine Valley' showing the long profile and described bank exposures and core samples

Table 2 ^{14}C dating results

Sample number	Location	Geomorphic unit and texture	Age
Waikato 12356	'Ralpine Valley' downstream of cessation of swamp	Bar form; very coarse granular and pebbly sand, in channel fill sequence	4653 ± 55 BP (Conventional ^{14}C date)
Waikato 12357	'Ralpine Valley' downstream of cessation of swamp	Bar form; very coarse granular and pebbly sand, in channel fill sequence	3966 ± 54 BP (Conventional ^{14}C date)
Waikato 12358	'Ralpine Valley' downstream of cessation of swamp	Floodplain fill. Very poorly sorted, coarse to very coarse and granular silty sand with minor pebbles disseminated throughout. Fines upward	4504 ± 55 BP (Conventional ^{14}C date)
Waikato 12359	Unnamed property adjacent to the 'Kings Highway' crossing of Mulloon Creek	Gravel lag/channel fill boundary	12080 ± 81 BP (AMS ^{14}C date)
Waikato 12360	Unnamed property adjacent to the 'Kings Highway' crossing of Mulloon Creek	Channel fill clay	12528 ± 89 BP (Conventional ^{14}C date)
Waikato 12361	Unnamed property adjacent to the 'Kings Highway' crossing of Mulloon Creek	Channel fill clay	12388 ± 65 BP (AMS ^{14}C date)
ANU 6822	'Ralpine Valley' swamp	Peat swamp	3690 ± 220 BP
ANU 10753	'Ralpine Valley' swamp	Peat swamp. Inferred channel fill	3440 ± 90 BP

At the entrance to this pocket, Mulloon Creek has bank heights greater than 3 m and a width of 20–25 m. As the valley widens downstream, banks decrease in height to approximately 2.5 m, and are composed of coarse pebbly sand overlain by fine to medium silty sand (RV1; Figure 3). The contemporary channel has a gravel and cobble bed with clast sizes of up to 30 cm. Mid-channel cobble bars and vegetated islands are up to 25 m long and 15 m wide. Chute channels actively rework basal gravels.

In mid-pocket, the channel is < 0.2 m deep and < 5 m wide, with fine silty sand and sporadic pebbles along its bed. Downstream, the channel breaks down into multiple stringers and a montane peat bog has formed. Today, this feature is structurally a grass bog as it consists of a grassland and

sedgeland with 30–50 cm high hummocks of *Poa costiniana* intergrown with numerous other herbs (Hope, 1998). The swamp generally slopes away to the valley margins, where drainage channels have been cut. Extensive slumping and dewatering features are evident across the swamp, with occasional abandoned, low capacity discontinuous channels.

A core from the middle of the floodplain, at the upstream limit of the swamp (RV2), shows 1.5 m of fining upwards silty sand and sandy silt with increasing organic matter content that grades into swamp sediments (Figure 3). In bank sections RV3 and RV4, which have up to 3.7 m of valley fill, basal gravels are overlain by an upward fining sequence of silty sand, with increasing clay (Figure 3). This unit, in turn, is overlain by up to 1 m of organic-rich (swamp) material.

Table 3 ^{210}Pb analysis results of post-incisional alluvium in 'Ralpine Valley' and Lower Mulloon floodplain pockets

Core	Sample no.	Sample depth		Excess ^{210}Pb activity				
		(cm)	(cm)	(Bq/kg)	(Bq/kg)	(%)		
LM7	D276	0.5	±	0.5	5.99267	±	1.00333	16.7
LM7	D277	12.5	±	0.5	0.79117	±	0.97483	123.2
LM7	D278	24.5	±	0.5	- 8.30350	±	1.91533	- 23.1
LM7	D279	36.5	±	0.5	- 6.89033	±	1.71250	- 24.9
LM7	D280	46.5	±	0.5	- 11.80177	±	4.25433	- 36.0
LM7	D281	59.5	±	0.5	- 2.24683	±	3.75333	- 167.0
RV1	D282	1.5	±	1.5	41.36983	±	3.28467	7.9
RV1	D283	19.0	±	1.0	- 21.35167	±	3.36100	- 15.7
RV1	D284	43.5	±	1.5	- 32.06350	±	3.87383	- 12.1
RV1	D285	51.0	±	1.0	- 38.19400	±	3.88317	- 10.2
RV7	D286	1.0	±	1.0	33.49650	±	2.23700	6.7
RV7	D287	21.0	±	1.0	- 0.26467	±	1.06783	- 403.3
RV7	D288	41.0	±	1.0	- 1.74233	±	1.64333	- 94.3
RV9	D289	1.0	±	1.0	32.33000	±	4.19400	13.0
RV9	D290	11.0	±	1.0	- 9.93300	±	3.97350	- 40.0
RV9	D291	21.0	±	1.0	- 37.86333	±	5.28550	- 14.0

Hope (1998) established the commencement of swamp formation in 'Ralpine Valley' at 3690 ± 220 BP (ANU 6822). A sample of swamp materials collected from a depth of 3.45 m depth returned an age of 3440 ± 90 BP (ANU 10753). The presence of swamp facies at this depth notably exceeds the depth of swamp facies exposed along contemporary banks (typically < 1.5 m), indicating that the swamp formed initially within a channel. Additional dates obtained in this study, from organic matter deposited in a channel fill sequence located immediately downstream of the contemporary swamp, yielded age estimates of 4653 ± 55 BP (Waikato 12356) and 3966 ± 54 BP (Waikato 12357) (see Table 2, Figure 3). The sequences indicate that a continuous channel was active for an extended period prior to swamp formation. Moving upwards, sediments contained within channel fills become progressively finer and more organic rich, possibly reflecting progressive decrease in channel capacity prior to the channel becoming discontinuous. Wood contained in fine to medium and silty sand (floodplain deposits in RV6, 1.1 m above the channel base), indicates that floodplain formation was well advanced by 4504 ± 55 BP (Waikato 12358; Table 2, Figure 3).

A major headcut, around 2.5 m deep, presently lies in the middle (swamp) section of 'Ralpine Valley'. This feature is now protected by a boulder ramp. Various smaller-scale (< 0.50 m) headcuts are evident upstream. Local knowledge indicated that incision proceeded rapidly following the cutting of deep drains at valley margins of the bog in 1988 (Peter MacAdam, personal communication, 2002). Following incision, the lower end of the bog has been dewatered and compacted, with extensive cracking evident. Basal gravels have been exhumed. Channel capacity increases markedly downstream of the headcut, extending up to 40 m wide. The channel has an array of pool/riffle sequences, lateral bars, dissected mid-channel bars and minor point bars where the low flow channel begins to meander within the macro channel.

The floodplain surface in the downstream section of the floodplain pocket is characterized by boggy ground with a typical thickness of organic-rich materials of < 0.25 m. Bank exposure RV5, downstream of the swamp, reveals a channel fill sequence in which interbedded silty sand and clayey silt grades into organic rich clay materials (Figure 3). This indicates that swampy conditions prevailed within the channel. In an adjacent bank exposure, RV6, the floodplain comprises upward fining deposits of silty sand and sandy silt atop basal gravels (Figure 3). These materials are overlain by < 0.2 m of silty clay with a poorly defined soil horizon. The latter unit is considered to represent post-incisional alluvium (ie, overbank deposits derived from reworking of floodplain/swamp deposits by the incised channel). In a downstream core (RV7), an equivalent upward fining sequence is topped by 0.76 m of post-incisional alluvium (Figure 3). This indicates that the post-incisional alluvium thickens markedly down-pocket. Outlines of multiple, high sinuosity channels with pools are evident on the floodplain downstream of the swamp zone. Seemingly, these features were abandoned as headcuts progressed through this area.

Excess ^{210}Pb analyses indicate that although incision has only recently proceeded into the central part of the swamp, generation of the lighter-textured, slightly coarser post-incisional alluvium commenced prior to European settlement (Table 3, Figure 3). In the upstream zone (RV1), where there is 0.41 m of post-incisional alluvium, there was no excess ^{210}Pb

activity at 0.19 m or below. Immediately downstream of the swamp (RV9), where 0.18 m of post-incisional alluvium has been deposited, there was no excess ^{210}Pb activity at 0.11 m or below. At the downstream end of the valley (RV7), where the post-incisional alluvium attains its greatest thickness of 0.76 m, there was no excess ^{210}Pb activity at 0.21 m or below.

'Mulloon Creek'

'Mulloon Creek' floodplain pocket, located 20.8 km from source, is 2.4 km long and has a maximum width of almost 0.3 km (Figures 1 and 4). The intervening 13.4 km from 'Ralpine Valley' is characterized by a confined valley with a series of entrenched meanders. This is the longest intervening distance between the major floodplain pockets. The 8 m sediment stack immediately downstream from the point of confinement is the thickest within the study area. Thickness of the valley fill decreases progressively down-pocket to a depth of around 2 m. The channel is typically around 50 m wide and comprises a bedrock-based pool-riffle sequence with occasional mid-channel and bank-attached bars. Shallow levees are locally evident. Abandoned channels of moderate sinuosity and decreasing capacity can be traced along the floodplain. In locally wider sections of the valley, contemporary swamps have formed at floodplain margins.

The upstream part of 'Mulloon Creek' floodplain pocket comprises upward-fining floodplain materials overlying basal gravels, with no evidence of swampy deposits or post-incisional alluvium (see MC1; Figure 4). Gravels are around 1 m thick. The presence of up to 1.7 m of organic-rich clay materials in mid-pocket bank exposures provides evidence for former swamp conditions, indicating that the channel broke down into a discontinuous watercourse in this area (see MC2; Figure 4). These deposits overlie upward-fining floodplain deposits, and are capped by up to 0.4 m of post-incisional alluvium.

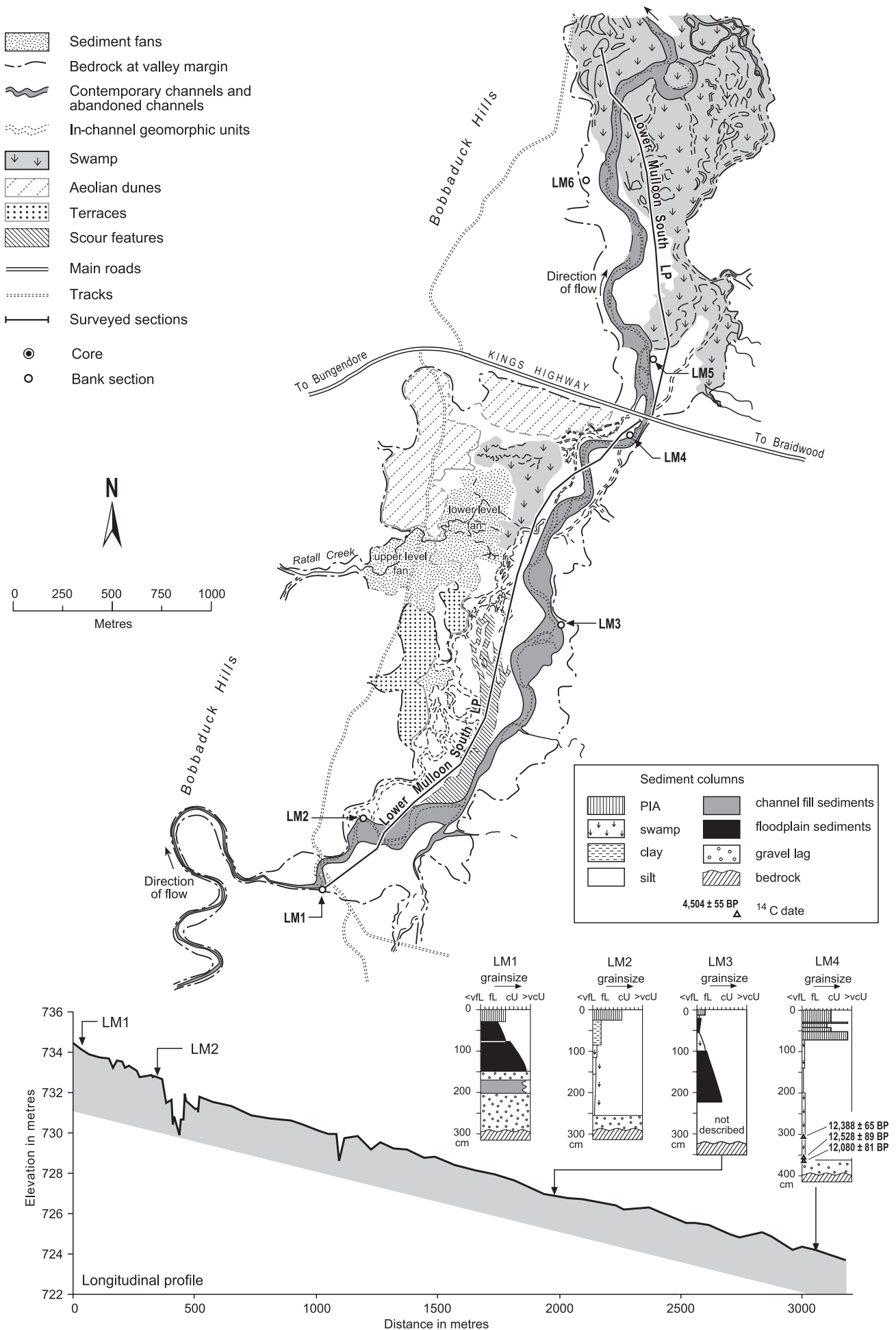
A sequence of cores taken along a cross-section in mid-pocket indicates the presence of swamp facies within a palaeochannel close to the valley margin, while the proximal floodplain shows little or no swamp development (see MC3, MC4 and MC5 on Figure 4). Multiple high sinuosity channels with numerous pools drained the downstream end of the swamp. These channels converged into a single channel where the stream re-entered confinement. Contemporary incision and channel expansion has stranded these palaeochannels and dewatered the swamp. The bank section at the downstream end of the floodplain (MC6) comprises interbedded gravel and fine-grained (floodplain) units capped by 0.82 m of post-incisional alluvium (Figure 4).

Lower Mulloon

The floodplain pocket at 'Mulloon'/'Mulloon Farm' and 'Palerang'/'Duralla Creek' extends over 10 km long and up to 1 km wide, separated by a bedrock high at Kings Highway (Figure 1). For ease of presentation, these pockets are presented separately (Figures 5 and 6). This pocket is 24.3 km from source, and is separated from 'Mulloon Creek' floodplain pocket by a 1.5 km reach of entrenched bedrock meanders.

The assemblage of geomorphic units at Lower Mulloon is similar to the other pockets. The low sinuosity channel varies in width from 35 m to 135 m. Terrace and fan deposits line much of the western valley margin. Aeolian dunes are evident

Figure 4 Distribution of geomorphic units at 'Mulloon Creek' showing the long profile and described bank exposures and core samples. The cross-section shows the greatest development of swamp deposits within the palaeochannel. Adjacent areas are characterized by minor swamp development and there is no swamp development at the valley margin. Post-incisional alluvium is also thickest with the palaeochannel and thins distally



adjacent to the confluences with Rataill Creek (Figure 5) and Sandhills Creek (Figure 6). Fan and dune deposits partially onlap the contemporary floodplain. The low flow channel occasionally meanders within the macro channel. The channel is characterized by a bedrock-based pool–riffle sequence with minor runs, and scour pools up to 2.5 m deep and 7 m wide. Compound point bars, lateral bars, dissected mid-channel bars and gravel sheets line the bed. Channel depth decreases in a fairly progressive manner down-pocket, seldom exceeding 3.5 m. High sinuosity, low capacity palaeochannels are evident, with poorly developed backswamps at valley margins. The Fairy Meadow parish map (1822) refers to the downstream end of this floodplain pocket as Long Swamp or Grubberdedrack Swamp. This swamp has been drained following recent incision. A continuous channel shown in the downstream 3 km of this floodplain pocket indicates that incision had commenced in the area downstream of this swamp prior to European settlement. Subsequent parish maps indicate that Long Swamp itself had been incised by a continuous channel prior to 1895. Multiple channels that dewatered the swamp coalesced to form a high sinuosity channel with multiple pools.

At the exit from bedrock confinement at the upstream end of the floodplain pocket, 0.29 m of sandy silt has been deposited atop a paleosol (LM1; Figure 5). The latter feature is the end member of the 1.2 m thick upward fining floodplain fill sequence that comprises basal gravels overlain by coarse sand that grades to silty sand and sandy silt with minor clay. Moving down-pocket, sediment sequences in a bank exposure at LM2 reveal around 1.5 m of fine-grained, organic-rich (swamp) materials that have accumulated within a palaeochannel (Figure 5). This overlies around 0.5 m of basal gravels and is capped by around 0.75 m of clay and 0.25 m of post-incisional alluvium. Bank exposure LM3 comprises an upward fining sequence in which basal gravels are overlain by 1.23 m of floodplain/swamp sediments, capped by 0.13 m of post-incisional alluvium (Figure 5). Basal gravels in a bank section at Kings Highway south are overlain by 0.70 m of laterally discontinuous sand beds, in which silt content increases up-profile (LM4; Figure 5). This channel fill sequence is capped by medium to heavy, organic-rich clay materials (ie, swamp deposits that formed within the former channel). A piece of wood found at the gravel/clay boundary yielded an age estimate of $12\,080 \pm 81$ years BP (Waikato 12360; Table 2). Charcoal samples from within the channel fill clay materials yielded age estimates of $12\,528 \pm 89$ years BP and $12\,388 \pm 65$ years BP (Waikato 12360 and 12361, respectively; see Table 2 and Figure 5). The channel fill sequence is overlain by 0.72 m of interbedded poorly sorted, medium to coarse and granular, silty sand, with sporadic pebbles. This is the thickest unit of post-incisional alluvium that is exposed south of Kings Highway. It is coincident with a localized valley constriction.

Downstream of Kings Highway, floodplain thickness is generally < 2 m, atop variable thicknesses of basal gravel (Figure 6). The depth of post-incisional alluvium in LM5, LM6 and LM7 is 0.30 m, 0.25 m and 0.44 m, respectively. While floodplain thickness diminishes down-pocket, with depths of just a few tens of centimetres, the thickness of post-incisional alluvium increases, attaining a maximum depth > 1 m in LM 8 (Figure 6). Thickness of post-incisional alluvium decreases dramatically away from the incised channel, attaining depths of a few tens of centimetres at valley margins (LM10; Figure 6).

^{210}Pb analysis from core LM7 indicates that only the uppermost portion of the sediment stack was deposited in the period since European settlement (Table 3). Samples taken at 0.05 m and 0.125 m returned excess ^{210}Pb activity, while samples taken at 0.245 m and below returned decreasing values for ^{210}Pb activity. This indicates that while 0.44 m of post-incisional alluvium has been deposited at this site, it is likely that only the sediment above 0.245 m has been deposited since European settlement. However, the error for the value of excess ^{210}Pb activity at 0.125 m in LM7 extends into the background value and therefore may not represent an accurate value showing actual excess ^{210}Pb activity (see Table 3).

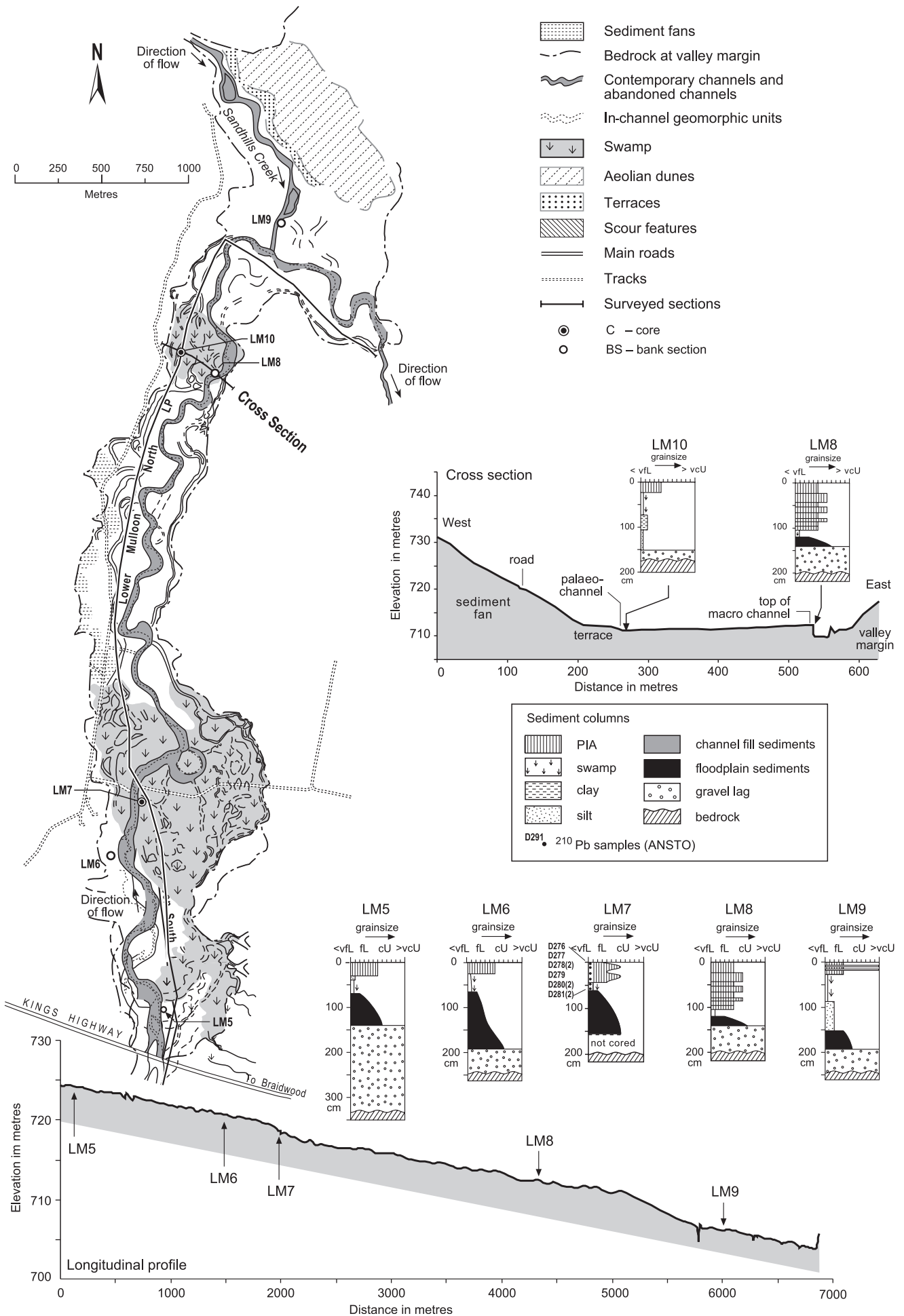
Late Quaternary floodplain evolution of Mulloon Creek

Sediment sequences in each floodplain pocket exhibit the same set of relationships, as summarized in Figure 7. The sediment stack thins notably down-pocket. For example, 'Mulloon Creek' floodplain pocket thins from around 8 m thick to around 2 m thick over its 2.4 km length. Laterally and longitudinally extensive basal gravels, typically < 1 m thick, are overlain by upward fining, vertically accreted floodplain deposits. As materials built up at the exit from the point of confinement, and extended down-valley and laterally, they generated a wedge-shaped sequence of fill deposits. Around the mid-Holocene, a swamp developed within the channel in mid-pocket, progressively colonizing the valley floor as the channel became discontinuous. Swamp formation was not continuous throughout each pocket. There is no evidence of swamp formation in the upstream zone of each pocket and downstream areas were perhaps characterized by relatively thin swampy ground (as noted in 'Galvin's Valley' today). The mid-pocket swamp acted as a sediment trap, accentuating the marked spatial variability in patterns and rates of sedimentation along the floodplain pocket.

Remnant swamps remain along upland floodplain pockets of Mulloon Creek, and they are presently being incised at 'Ralpine Valley'. Development of a continuous incised channel through swamp units and the underlying valley fill in downstream floodplain pockets has released fine-grained materials. The marked decrease in thickness of valley fill deposits down-pocket has ensured that the incised channel becomes much shallower and wider down-pocket (Figure 7). As a consequence, post-incisional alluvium forms a wedge-shaped unit that thickens down-pocket atop the underlying floodplain from the headcut. As a channel existed at the downstream end of these floodplain pockets prior to the arrival of Europeans, it is inferred that incision of valley fill deposits was initiated prior to European settlement, but it was accentuated by human disturbance.

The late Quaternary evolution of floodplain pockets along Mulloon Creek is reconstructed in Figure 8. Prior to 12 500 years ago, the system operated as a bedload-dominated river, transporting clasts up to 15 cm. By mid-Holocene, the system had been transformed into a discontinuous watercourse, with swamp features in mid-pocket. Swamps were evident in all floodplain pockets at the time of European settlement of the region (c. 1820), and continue to be retained in an intact and partially intact condition in upstream pockets ('Galvin's Valley' and 'Ralpine Valley', respectively). However,

Figure 5 Distribution of geomorphic units at Lower Mulloon South showing the long profile and described bank exposures and core samples. Figure 6 adjoins at the northern edge. Figure 4 adjoins at the southwest corner. Swamp deposits depicted in LM2 and LM4 are indicative of swamp formation within stable, longstanding channels



within a few decades of settlement, the swamp in downstream floodplain pockets had incised, creating a continuous gravel-bed, low sinuosity channel.

The character and age of channel fill deposits that lie immediately above basal gravels (dated at $12\,528 \pm 89$ years BP; Waikato 12360), indicate a marked shift in depositional conditions from those in which extensive, but thin, gravel sheets were reworked along the valley floor. Basal gravels have a relatively uniform thickness of around 1 m. Seemingly, this veneer of coarse gravels and cobbles was reworked from a former valley fill. The undulating form of these gravels is considered to represent the outline of former bar and shallow channel features, perhaps representing a braided channel configuration (Figure 8, Stage 1). It is inferred that climatic conditions around the last glacial maximum (LGM) destabilized valley floors and stripped away floodplain deposits. Downstream-thinning terrace remnants that are preserved in embayments, over-widened areas or behind bedrock highs and spurs are considered to indicate that, prior to the LGM, floodplain sediments filled the valleys to a greater extent than is evident today (Figure 8, Stage 1). Based on this premise, all fine-grained materials that made up former floodplains, other than terrace remnants, were flushed through these valley settings.

The presence of a black, organic-rich clay unit within a channel fill sequence (basal age $12\,528 \pm 89$ years BP, Waikato 12360; Figure 5) that directly overlies the gravel lag indicates that a major change in the type of sedimentation (or preservation) occurred some time prior to 13 ka BP. Seemingly, a laterally unstable, gravel-bed river was transformed into a suspended load system in which fine-grained materials infilled former channels, initiating floodplain formation via vertical accretion (Figure 8, Stage 2). Prosser *et al.* (1994) dated a similar transition in patterns of sedimentation in Wangrah Creek to $12\,420 \pm 150$ years BP. Along Mulloon Creek, the altered depositional conditions promoted the development of a wedge-shaped valley fill, in which rates of sedimentation diminished markedly down-pocket and distally. Thin, discrete layers of small pebbles are evident within proximal floodplain deposits while distal floodplains slowly accumulated finer sand and silt. The limited extent of infilling of palaeochannels is testimony to the low rates of floodplain sedimentation.

Swamp deposition within the channel fill, in the form of a peat bog, commenced at least 3700 years ago at 'Ralpine Valley' (3690 ± 220 years BP; ANU 6822; Hope, 1998; Figure 3). Initially, channel infill deposits comprised bed load material, but these were progressively replaced by suspended load organic-rich silt and clay (Figure 8, Stage 3). The reduction in flow energy in mid-pocket enabled aquatic vegetation to colonize the channel. Contemporary bed slope is around 0.0185 in this area, notably gentler than at the upstream end of the pockets where slopes average 0.026 (see longitudinal profiles on Figures 2–5). Seemingly, loss of energy associated with reduction in slope promoted instream sedimentation that further reduced channel capacity, such that the channel eventually became discontinuous. As a consequence, flows increasingly went overbank, dissipating their energy on the floodplain. Once swamp formation was firmly established within the channel, swamp conditions developed across the central portion of the floodplain pocket.

The efficiency of sediment trapping in mid-pocket reduced the downstream transfer of materials, further reducing the rates of sedimentation at the bottom end of the floodplain pockets and enhancing the downstream-thinning, wedge-shaped morphology of the valley fill. In down-pocket areas, floodplain deposits are thin, with only the beginnings of rudimentary swamp deposits in distal valley margin depressions. Multiple, high sinuosity channels dewatered the swamp. These low capacity channels progressively infilled with fine-grained, organic-rich material. At the toe of the swamp, these small channels coalesced into a continuous, low capacity channel, with numerous pools. In this area, channel-marginal sediments comprise fine silts and sands while valley marginal sediments are silty clays.

Any factor that promotes bed level instability has the potential to generate a headcut (see Schumm *et al.*, 1984). Once initiated, these features are exceedingly difficult to stop. Following European settlement of the area, reduction of vegetation cover and enhanced runoff rates, along with the presence of a continuous channel at the downstream end of floodplain pockets, stimulated headcut development. This activity was likely accentuated by a series of devastating floods on the southwest slopes and southern highlands of New South Wales between 1851 and 1879 (Barry Starr, personal communication, 2003). Although equivalent floods doubtless occurred throughout the Holocene, valley floors were sensitized to change following human disturbance, such that pronounced geomorphic adjustments took place as soon as formative events were applied to the modified ground surface. Similar findings are reported by Goede (1972). Local over steepening of slope along this discontinuous watercourse concentrated flow energy within the incised channel, thereby accentuating the rate of incision and up-valley retreat (Figure 7, Stage 4). As the headcut and incision channel travelled through the pocket, the swamp and floodplain fill were incised and dewatered. As the channel did not have the capacity to contain all flows downstream of the headcut, overbank flows generated vertical accretion deposits.

Since European settlement, the pre-existing high sinuosity, low capacity channels and the swamp have been replaced by a continuous, low sinuosity, overwidened channel that is incised to bedrock and is reworking basal gravels (Figure 7, Stage 4). Whereas once these upland swamps and floodplains acted as sediment sinks, regulating the sediment flow to downstream reaches, the concentration of stream power within the contemporary channel mobilizes and flushes all but the coarsest fraction through the system. This coarse fraction is stored within the overwidened channel as compound bars and gravel sheets.

Channel width–depth ratio increases markedly down-pocket, from < 10 at the upstream end to > 20 at the downstream end (Figure 7). Wedge-shaped deposits of post-incisional alluvium thicken downstream as channel depth decreases, creating an inverse wedge shape relative to the Holocene floodplain deposits that they overlie. Increases in channel connectivity following European settlement, and associated channel incision and expansion, have progressively decoupled the channel from the floodplain, decreasing rates of overbank sedimentation. Indeed, deposition of post-incisional

Figure 6 Distribution of geomorphic units at Lower Mulloon North showing the long profile and described bank exposures and core samples. Figure 5 adjoins at the southern edge. Swamp deposits are thickest within the palaeochannel (see cross-section). Minor, poorly developed, swamp development occurs close to the valley margin (LM8). Post-incisional alluvium is thickest proximal to the incision channel, thins distally and partially infills the palaeochannel at the valley margin. The terrace at the valley margin has been almost completely interred by contemporary floodplain and fan deposits

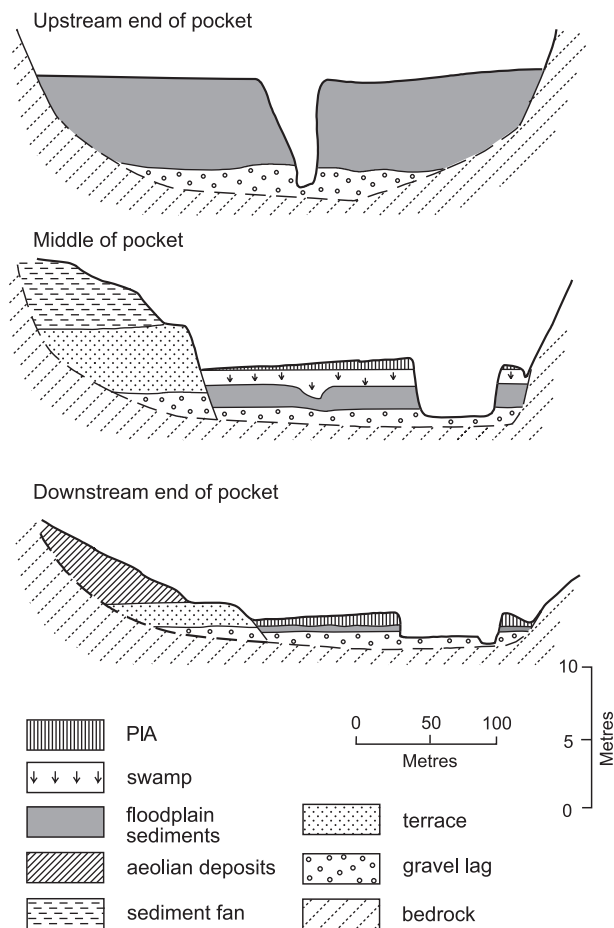


Figure 7 Schematic representation of down-pocket variability in channel geometry and bank sedimentology along Mulloon Creek

alluvium has all but ceased as the contemporary channel has sufficient capacity to contain all but the largest flows.

Discussion and implications

In general terms, a tendency for progressive (though intermittent) decline in rates of geomorphic river activity has been inferred across southeastern Australia during the late Quaternary (Nanson *et al.*, 2003). Along Mulloon Creek, the presence of elevated terraces, and floodplain margins that are overlain by source-bordering dunes, indicates that multiple phases of incision and reworking of floodplain sediments have occurred over various timescales in this landscape setting. This attests to a longer-term history of cut-and-fill river activity, the record of which is selectively preserved along differing sections of the floodplain pockets. Indeed, work along the Shoalhaven trunk stream by Nott *et al.* (2002) indicates that cut-and-fill river activity in this area extends back at least 500 000 years, and perhaps as far back as the Oligocene.

Sequences of valley floor deposits that thin notably down-valley, with a marked wedge-shaped morphology, have been described for various landscape settings in southeastern Australia, both above the escarpment (eg, Prosser *et al.*, 1994) and below it (eg, Fryirs and Brierley, 1998; Fryirs, 2002). Unlike the situations described by Prosser *et al.* (1994) and Fryirs and Brierley (1998), there is no evidence for multiple phases of cut-and-fill river activity preserved in the Holocene record of floodplain deposits along Mulloon Creek. In this instance, progressive sediment accumulation is inferred to have occurred at markedly variable rates within each floodplain

pocket throughout the Holocene, with a recent incisional phase that has been accentuated by human disturbance since European settlement.

During the Holocene, three primary phases of (dis) connectivity of bedload sediment conveyance can be highlighted from this case study. Throughout the early–mid Holocene, floodplain pockets acted as sediment accumulation zones, building downstream-thinning wedges of sediment beyond the point of confinement at the entrance to the pocket. Generation of mid-pocket swamps in the mid-Holocene inhibited sediment conveyance, as the swamp acted as a sediment trap. Finally, since European settlement, connectivity has been enhanced by generation of a continuous channel through the valley fill deposits.

Patterns of alluvial sedimentation along upper, middle and lower parts of the floodplain pockets along Mulloon Creek preserve quite different records of Holocene river activity. Down-pocket and lateral variability in floodplain sediment ensures that interpretations of river history vary markedly dependent upon the specific locations in which analyses are performed. This consideration has marked implications for the assessment of phases of river activity in cut-and-fill landscapes, requiring that great care must be taken in relating river adjustments to climate changes (eg, identification of cut and dry phases, *sensu* Nanson *et al.*, 1992). Phases of sediment storage and transport in tributary systems such as Mulloon Creek, and in headwater catchments generally, regulate downstream sediment supply to the trunk stream. The intermittent nature of sediment delivery from tributary systems, as determined by differing phases of swamp development in this system, ensures that the timeframe of cut-and-fill cycles in tributary catchments may differ markedly from that experienced along the trunk stream. Complexity in stratigraphic relationships is compounded further by non-synchronicity in cycles of incision in headwater catchments, as illustrated by Eyles (1977), Wasson *et al.* (1998) and Prosser and Winchester (1996). Along Mulloon Creek, the wedge-shaped floodplain deposits have acted as a form of drainage breakdown throughout most of the Holocene, disconnecting sediment transfer from upper parts of this tributary system to the trunk stream. This effect is accentuated when lobes of sediment accumulate atop swamp features in mid-pocket, creating a form of floodout (Melville and Erskine, 1986; Fryirs and Brierley, 1998; Tooth, 1999; Gore *et al.*, 2000).

The valley fill along Mulloon Creek extends the spectrum of morphological and floodplain sedimentology that has been reported for variants of discontinuous watercourses in the region (eg, chains of ponds, Eyles, 1977; incised channels, Bird, 1982; dells, Young, 1986; swampy meadows, Prosser *et al.*, 1994). Given the nature and evolutionary history of these differing forms of discontinuous watercourses, there is significant variability in their sensitivity to disturbance, and resulting off-site consequences. The relatively thin, fine-grained nature of valley fill deposits along Mulloon Creek has ensured that significant changes to river forms and processes recorded since European settlement have not had the same magnitude of off-site responses that have been recorded along river courses elsewhere in the region (eg, Brierley *et al.*, 1999; Rutherford, 2000). Indeed, a significant proportion of materials released following incision has likely been flushed through the system, with limited morphological implications. The relative resilience to change of this variant of discontinuous watercourse is emphasized by the maintenance of an intact swamp in the most upstream setting ('Galvin's Valley'), while the next major pocket downstream presently contains a major headcut ('Ralpine Valley'). The pattern of disturbance responses

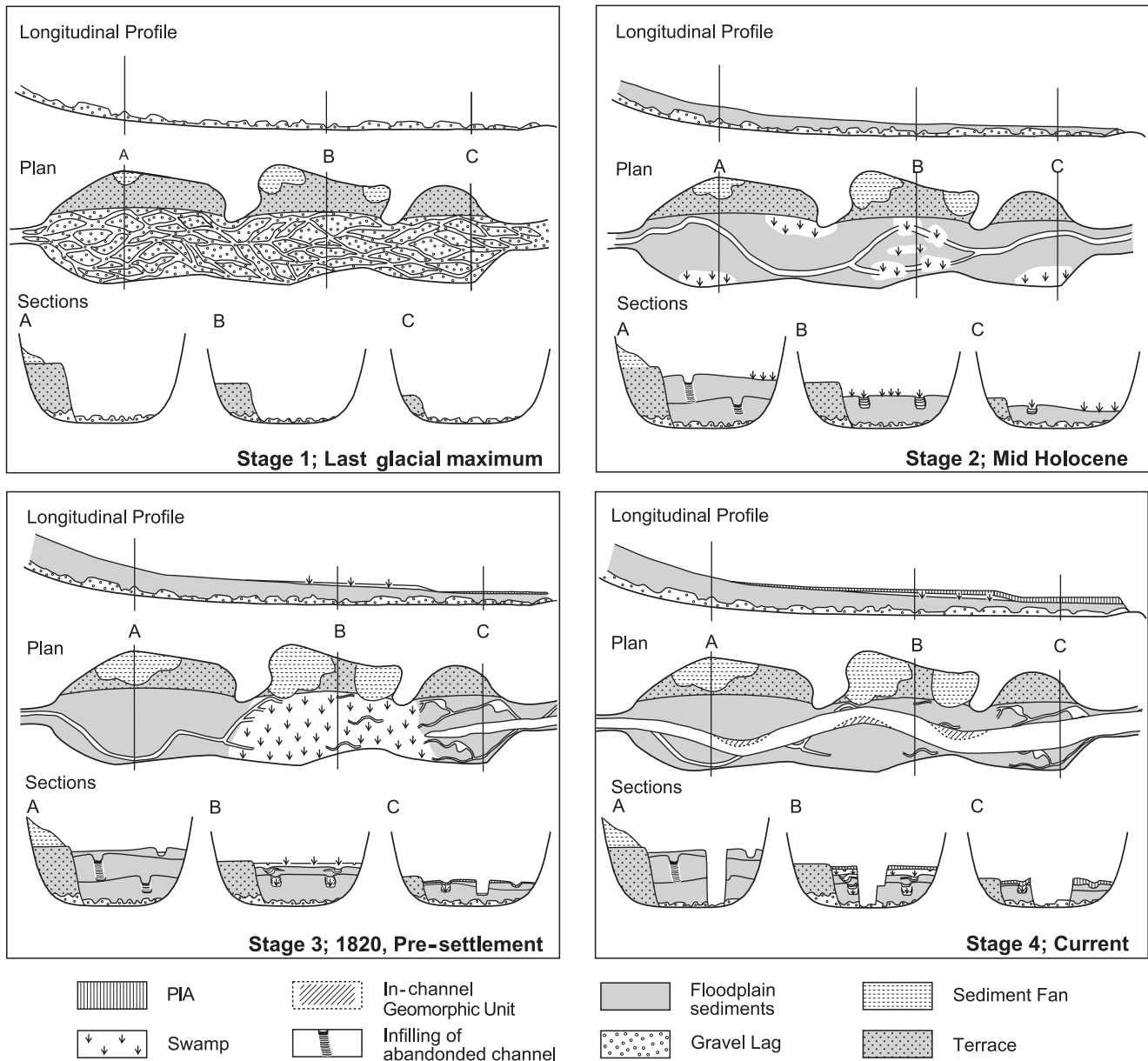


Figure 8 Schematic representation of late Quaternary floodplain evolution of Mulloon Creek. Stage 1 depicts the maximum extent of sediment reworking inferred to have occurred at the last glacial maximum. Braidplain gravels are generally of uniform thickness. Remnant terraces at the valley margin thin down-pocket. By mid-Holocene, vertically accreted valley fill deposits have extended down-pocket as sediment lobes with perched channels, similar in form to floodouts which periodically avulse (Stage 2). Swamp formation, which was initiated within the channel, begins to colonize the valley floor. Distal areas are poorly drained and comprise boggy ground rather than swamps. Sedimentation at the head and centre of the pocket starve the downstream areas of sediment, forming a wedge-shaped deposit that decreases in thickness down-pocket. This wedge-shaped floodplain reaches its maximum extent around the time of European settlement (Stage 3). Extensive swamp development is evident in mid-pocket. A channel drains the downstream part of the pocket. This channel extended through the pocket shortly after European settlement (Stage 4). Today, a wedge-shaped unit of post-incisional alluvium thickens down-pocket, commencing in mid-pocket atop the swamp facies

reported in this study likely reflects the combination of more limited human impacts in upstream reaches (where floodplain pockets are much smaller) and the low stream power in these settings (because of lower catchment area).

The contemporary channel geometry of Mulloon Creek has been influenced by the nature of the valley fill (Figure 7). Down-pocket variability in bank stratigraphy reflects differing forms and stages of Holocene sedimentation. As a consequence of incision, contemporary channels have composite banks, characterized by basal gravels (potentially of considerable antiquity) with finer-grained materials atop. The hiatus between the timeframe of origin of bed and bank materials,

and related trends in channel size and shape, the nature of bank stratigraphy, bed material size and flood inundation heights, varies down-pocket. At differing phases of channel incision, the nature of bed and bank materials changes, reflecting former phases of deposition. Hence, contemporary river adjustments must be viewed in context of long-term controls on the character and patterns of valley floor sedimentation.

Ultimately, geological influences have exerted local control on base level and valley width of each floodplain pocket, limiting the depth and lateral extent of valley fill (Tooth *et al.*, 2002). Maximum thickness of each floodplain pocket is

determined not only by catchment area, but also by the proximity of the preceding pocket upstream, which acts as a sediment storage zone. The greater the distance between pockets, the greater the thickness of floodplain fills at the upstream end. These factors, in turn, have determined the extent/rate of incision, the volume of sediment released from each floodplain pocket, patterns of deposition following incision (ie, the distribution of post-incisional alluvium) and contemporary channel geometry. Today, many of these channels are able to flush all but the coarsest sediments, leaving relatively small volumes of lag materials as gravel sheets, compound point bars and lateral bars within the overwidened incised channel.

These findings reaffirm the contention that unravelling the past provides a key to explaining the present, thereby aiding assessments of how river systems are likely to adjust in the future. Long-term (geological) controls on the emplacement of floodplain pockets, along with late Quaternary controls on the pattern of sediment deposition along valley floors, have influenced the character and behaviour of the contemporary system, and the nature and rate of geomorphic river adjustments following European settlement. In a sense, landscape inheritance along Mulloon Creek can be differentiated in terms of differing forms of geologic, geomorphic and anthropogenic memory.

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